



# Overview and Responses to Recommendations

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2/17/14



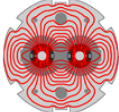
# Outline

- Magnets Systems: new goals and WBS
- MQXF Requirements & Development
- Other LARP work: MQXF risk reduction
- Responses to Recommendations



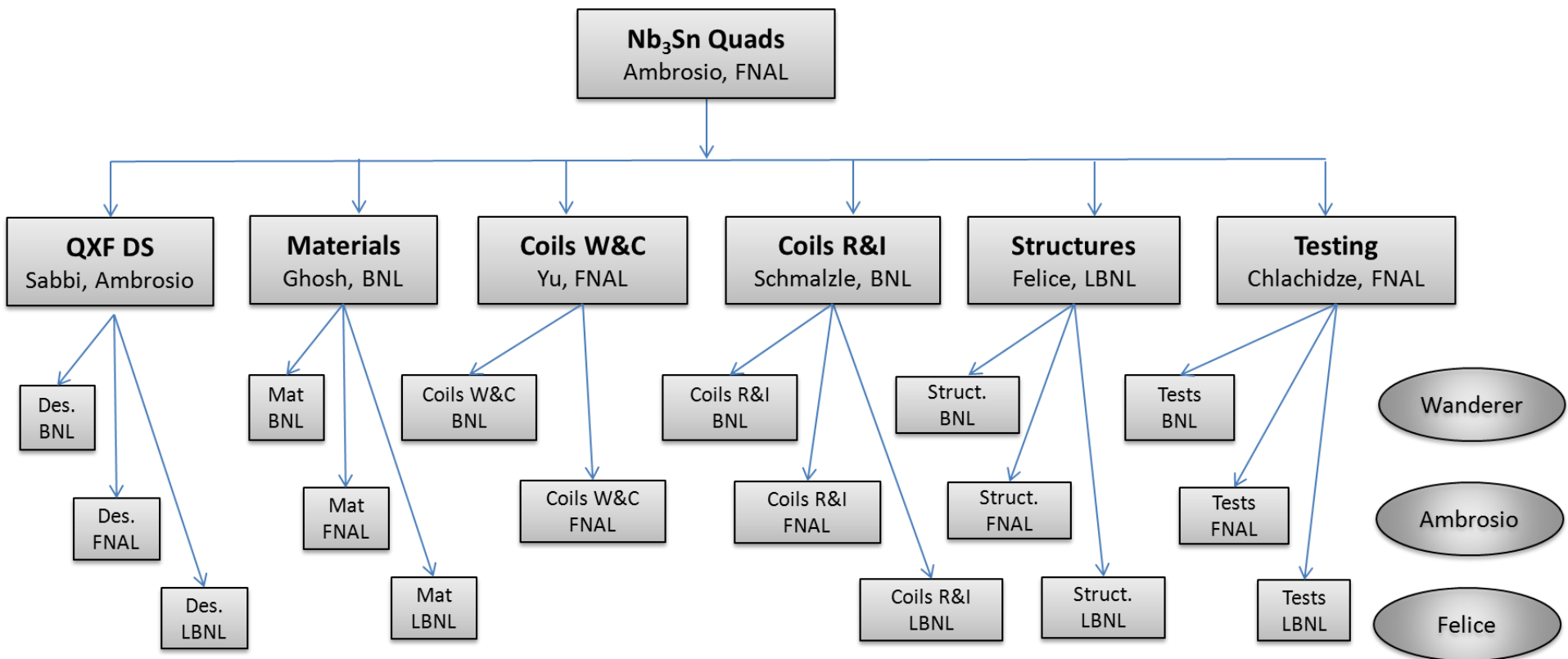
# Magnet Systems 2.0 - Goals

- Develop MQXF design and fabrication procedures
- Demonstrate readiness for construction project
  - Short/Long prototypes (S/LQXF)
- Reduce risks of construction project
  - HQ and LHQ in FY14; SQXF from FY15
  - Strengthen competencies at each lab for construction project
- Prepare for construction project
  - Documentation, QA, some infrastructure upgrade

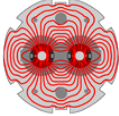


LARP

# Magnet Systems 2.0 – Org. Chart



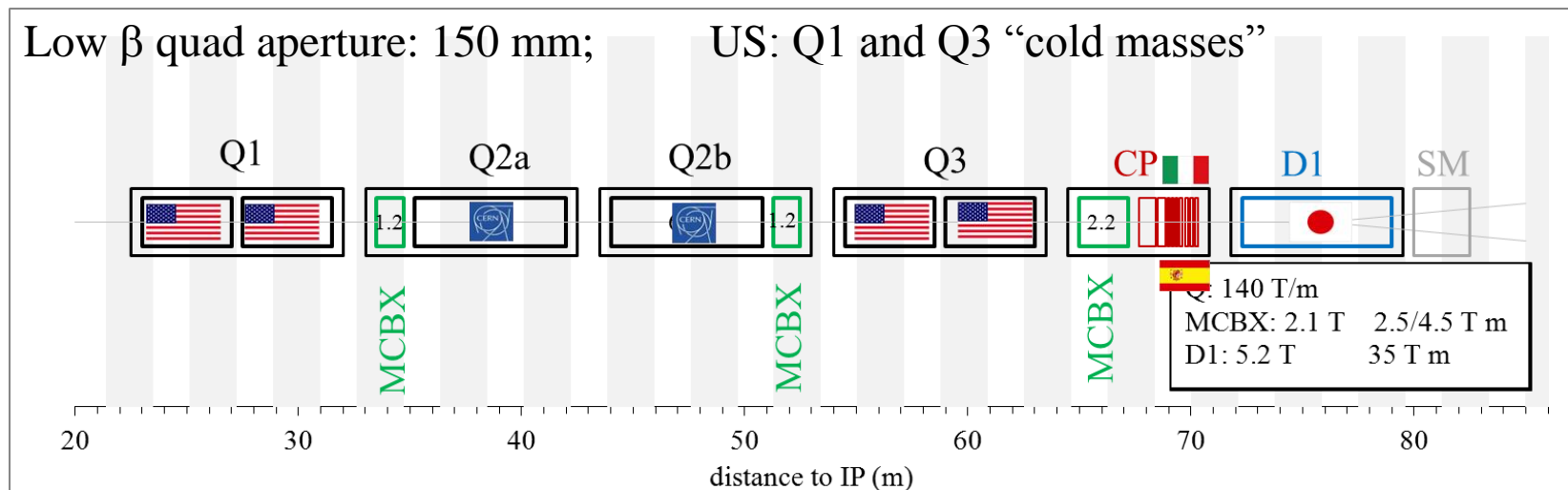
- L3s are coordinating QXF functions
  - In FY14 we have also HQ (Sabbi) and LHQ (Bossert)
- QXF coordinator/lab
  - Coordination, prioritizing, step toward CAMs

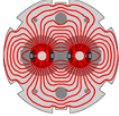


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# MQXF Requirements

- Requirements are being set by the WP3 of the HiLumi Project:
  - G. Sabbi (LARP) is co-chair
  - Significant LARP contribution
    - Some examples in next slide and next talks
  - <https://espace.cern.ch/HiLumi/WP3/SitePages/Home.aspx>





# MQXF Requirements II

- Example of LARP contribution:
  - Impact of field quality on dynamic aperture



Field quality specifications for IT quadrupoles  
at collision energy ( $r_0 = 50$  mm)



Blue values are estimates of the field quality based on magnet design. Red values are adjustments (reduced relative to the estimate) needed for sufficient dynamic aperture (DA).  
Reference table: "IT\_errortable\_v66".

skew	mean	uncertainty	random	normal	mean	uncertainty	random
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a13	0	0.010	0.010	b13	0	0.0072	0.0072
a14	0	0.005	0.005	b14	-0.020	0.0115	0.0115

More details in  
backup slides

HQ talk will show  
plan for meeting  
FQ requirements

$$B_y + iB_x = 10^{-4} B_{ref} \times \sum_{n=1}^{\infty} (b_n + ia_n) \left( \frac{x + iy}{r_0} \right)^{n-1}$$

# MQXF Development

- LARP is developing MQXF magnets in collaboration with CERN
  - Same design for US and CERN MQXF
  - ➔ We will benefit from prototypes built by CERN (and vice versa)
- Design and fabrication technology are based upon the successful LARP R&D
  - With contribution from CERN and US core programs

# Technology Demonstration Chart

2004

**Subscale Quadrupole**  
**SQ**  
0.3 m long  
110 mm bore

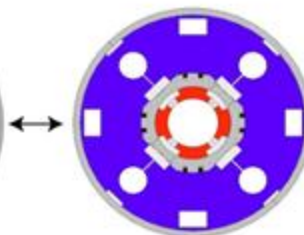
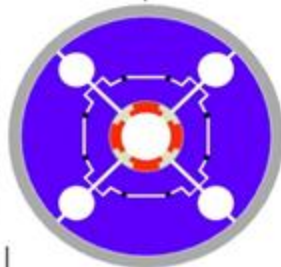


**Subscale Magnet**  
**SM**  
0.3 m long  
No bore

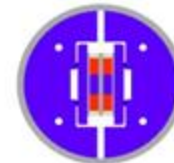


2005

**Technology Quadrupoles**  
**TQS, TQC**  
1 m long  
90 mm bore

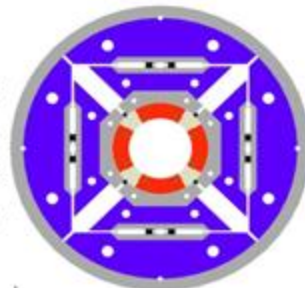


**Long Racetrack**  
**LRS**  
3.6 m long  
No bore

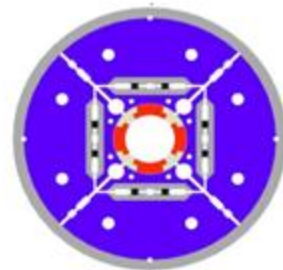


2008

**High Field Quadrupole**  
**HQ**  
1 m long  
120 mm bore



**Long Quadrupole**  
**LQS**  
3.7 m long  
90 mm bore



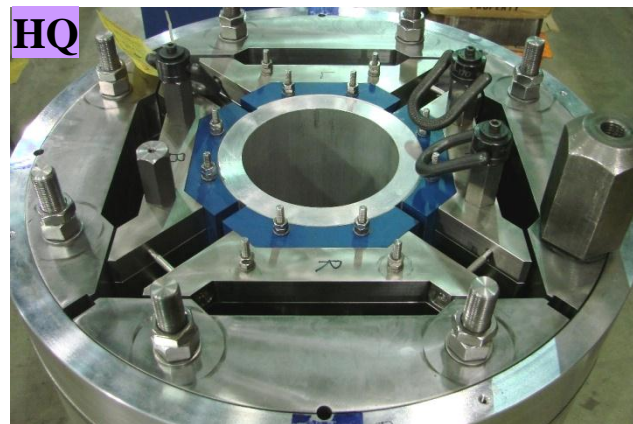
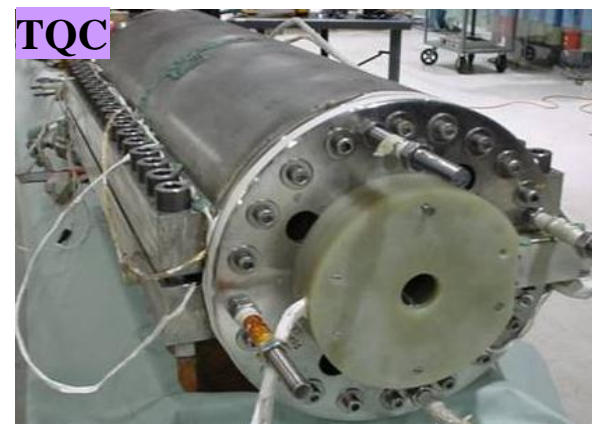
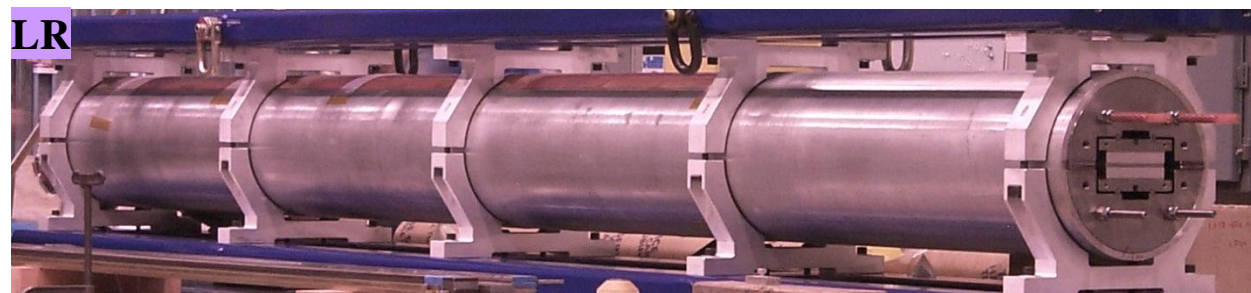
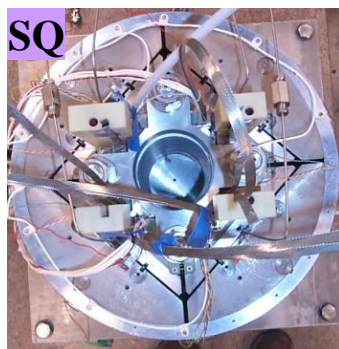
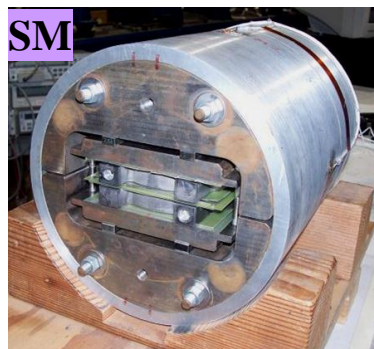
2011

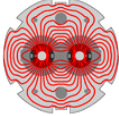
**Long High-Field Quadrupole (LHQ)**

3.7 m long coils



# Overview of LARP Magnets





# LARP Achievements

See extended list in  
back up slides

## R&D phases:

- 2004-2010: **technology development** using the SQ and TQ models
- 2006-2012: **length scale-up** to 4 meters using the LR and LQ models
- 2008-2014: incorporation of **accelerator quality features** in HQ/LHQ

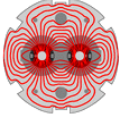
## Field gradient performances:

target (T/m)    **reached (T/m)**

- **TQ** models (90 mm aperture, 1 m length)    200    **240**
- **LQ** models (90 mm aperture, 4 m length)    200    **220**
- **HQ** models (120 mm aperture, 1 m length)    170    **184**
- **Excellent training memory**

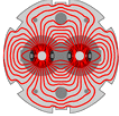
## Other achievements:

- Field quality: demonstrated **effectiveness of stainless core** (HQ02)
- Coil stress: mapped **safe stress range** (TQ03)
- Quench protection: demonstrated **photo-etched heaters** for protection of long Nb<sub>3</sub>Sn magnets (LR and LQ)



# LARP MS Effort

- LARP MS effort is exclusively focused on MQXF design, development and risk reduction
- HQ and LHQ coils are being used in FY14 for MQXF risk reduction
  - HQ budget: 13% of MS budget
  - LHQ budget: <5% of MS budget



# Risk Reduction Ex 1: LHQ

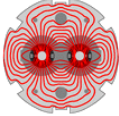
The LHQ program was reduced to 3 long coils, and one coil test.

- Coils: 3.4 m long; 120 mm aperture

The objective is to mitigate risk for the MQXF by:

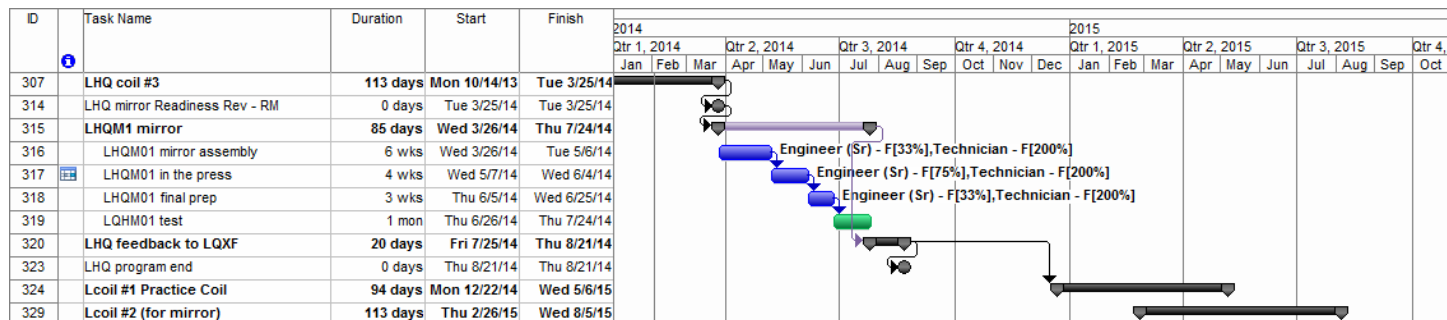
- Incorporating and testing features of QXF coils never tested in long Nb<sub>3</sub>Sn coils.
  - Cable with stainless steel core (in HQ02 coils)
  - Cable with braided insulation (in some HQ02 coils; in all HQ03 coils)
  - Cable with titanium doped strands
  - Stainless steel end parts (in all HQ coils)
  - Binder curing to avoid popped strands during end winding
  - More flexible end parts & temporary saddles
- Comparison of different protection heaters to select and calibrate the heaters for MQXF protection (only area that still needs some development)



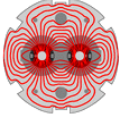


# LHQ Coil Fabrication Results

- 3 coils completed. Winding and curing was done at Fermilab, with Reaction and Impregnation at BNL.
  - 2 practice coils:
    - Used to optimize fabrication processes and tooling
    - One coil used to test end parts and saddles with flexible features
    - One coil passed and exceeded QXF electrical QA tests
    - Thorough autopsy for impregnation and end-part feedback
  - 1 coil to be tested in mirror structure:
    - Test planned at FNAL this July



# Responses to recommendations



**LARP**

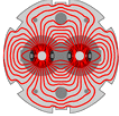
*2011 Review – Recommendation #1 on MS: The panel again **strongly** recommended that, during the coming year, in close consultation and cooperation with CERN, LARP undertake a substantial role for modeling energy deposition and radiation damage from beam losses and other collider issues related to the IR quad aperture decision*

*2012 Review – Recommendation #1 on MS: Seek access and/or collaboration with one or more of the venues with appropriate experimental facilities to broaden the database on radiation damage.*

There has been a lot of progress on this subject. Work was performed in collaboration with CERN, with the help of other experts (for instance Flukiger, and Weber) and dedicated workshops (WAMSDO 2011, RESMM12/13). The work was performed along these lines: thorough analysis of available data; experimental campaign under the EuCARD program. **This work has shown that Tungsten absorbers centered in the midplanes of magnet aperture can keep the integrated dose for 3000 fb<sup>-1</sup> as low as the dose for the present LHC low beta quadrupoles at 300 fb<sup>-1</sup>. The materials presently used for LARP coil fabrication technology can withstand this level of dose with sufficient margin.**

Work is in progress to assess that all auxiliary materials to be used in the MQXFs (for instance instrumentation wires and quench heaters) can withstand the expected dose with sufficient margin.

More details in last talk  
of this session



**LARP**



*2011 Review – Recommendation #2 on MS: LARP/APUL magnet program should develop a detailed plan including budget and schedule to advise DOE on future transition to an HL-LHC construction project.*

Such a plan has been developed for the Magnet System and was presented in the June 2013 Internal LARP Review. More on this point under “Management”.

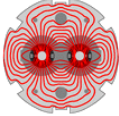
*2011 Review – Recommendation #3 on MS: Begin integrating cryogenic and cryostat design into the magnets.*

Following the 2012 DOE-LARP-CERN negotiation on possible US deliverables for the HL-LHC project, it was determined that the US would deliver quadrupole cold masses to CERN. Cryogenic and cryostat integration are a CERN responsibility. In 2012 CERN initiated the cryogenic design of the upgraded IRs and in 2013 they generated preliminary cryogenic requirements for the MQXFs (for instance, number and dimensions of the heat exchanger through the magnet yoke) which **have been taken into account in the present QXF design.**

Appropriate interactions with CERN will assure that the final design will meet all the requirements.

Several examples  
in next talks





*2011 Review – Recommendation # 4 on MS: If possible seek qualified alternate strand vendors and improve piece length*

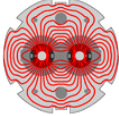
This task is being pursued by CERN, who is developing the PIT (Powder In Tube) conductor through the European manufacturer Bruker-EAS. **The QXF cable design has been developed jointly by LARP and CERN in order to keep open the option of using the PIT conductor.**

More details in 1<sup>st</sup> talk of 2<sup>nd</sup> session

*2012 Review – Recommendation #2 on MS: Quickly bring the effort on the 120 mm LHQ to an orderly conclusion and begin work on the 150 mm quad development.*

Done. The work on the QXF (150 mm aperture quad) received the highest priority right after the review. The design of the first short model (SQXF1) is almost complete. At the end of last year (2013) we started QXF winding tests, and we are now starting the fabrication of SQXF practice coils.

**The LHQ program was redirected toward risk reduction for the LQXF coils (full length QXF prototype) and reduced to 3 coils and one single coil test.** The fabrication of the third coil is to be completed in February 2014 and the LHQ coil test, planned for this spring, is bringing the LHQ development to its end.

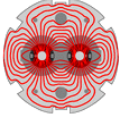


*2012 Review – Recommendation #3 on MS: Produce a resource loaded schedule that establishes the path to the final production of the required number of 150 mm quadrupoles to ensure that resources are properly utilized by November 30, 2012.*

**A resourced loaded schedule for the production of the required MQXF was developed and presented at the LARP internal project review (FNAL, June 2013). To paraphrase the reviewers statement in the final report (attached as addendum #1):**

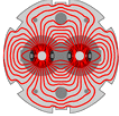
- a. The technical feasibility of the quad program seems reasonable.
- b. The costs have a decent basis in the LARP R&D program.
- c. The scope is reasonable for a \$200M US contribution.
- d. The major uncertainties and risk appear to be programmatic in nature.

We are in the process of loading resources to the schedule for the development of the prototypes. A draft for FY14 is available and is being used to check consistence between the cost estimate through the resources loaded schedule and estimates based on past LARP experience.



*2012 Review – Recommendation #4 on MS: Develop an acquisition strategy which seamlessly transitions from a research program into a construction project by November 30, 2012.*

A plan for the acquisition strategy will be developed for the US-HL-LHC Project. **A draft plan of the acquisition strategy including a conductor procurement plan was presented at the June 2013 LARP Internal Project Review.** Interactions with CERN and all stakeholders to finalize the deliverable (single structure/ single structure with helium shell/ full cold mass with two structures and helium vessel) are taking place. Consistency with the proposed overall LARP budget profile and plans will be checked and more details will be presented during this review



# MS Session

## QXF strategy:

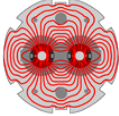
- Building upon solid foundation
- Minimizing development focused on risk areas
- Reducing risks
- Demonstrating readiness

### *Magnet System Session 1*

- 10:10 Overview and Responses to Recommendations 40'
- 10:50 HQ program status and results 40'
- 11:30 QXF Design Fabrication and Irradiation Studies 30'

### *Magnet System Session 2*

- 15:05 QXF Conductor and Cable 30'
- 15:35 QXF Coil Design and Winding Tests 20'
- 15:55 QXF Coil Fabrication and Tooling 20'
- 16:15 QXF Support structure design and development 30'
- 16:45 QXF Quench protection 20'
- 17:05 QXF schedule and preparation for project 20'



# Acknowledgement

M. Anerella, J. Cozzolino, J. Escallier, A. Ghosh, R. Gupta, H. Hocker, P. Joshi, P. Kovach, A. Marone, J. Muratore, J. Schmalzle, P. Wanderer.

BNL

G. Ambrosio, G. Apollinari, R. Bossert, R. Carcagno, G. Chlachidze, J. DiMarco, S. Krave, N. Mokhov, A. Nobrega, I. Novitski, R. Rabehl, C. Sylvester, M. Yu, A. Zlobin.

FNAL

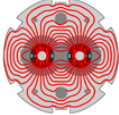
H. Felice, F. Boragnolutti, D. Cheng, D.R. Dietderich, A. Godeke, R. Hafalia, M. Marchevsky, I. Pong, S. Prestemon, G. Sabbi, X. Wang.

LBNL

Y. Cai, Y. Nosochkov, M.-H. Wang

SLAC

and I am sure I am missing someone...



*LARP*



# Back up Slides

# Introduction

- Collision optics of the HL-LHC will create very high  $\beta$ -functions in the inner triplet (IT) quadrupoles and the adjacent magnets. This requires an upgrade to large aperture superconducting (SC) magnets: Nb<sub>3</sub>Sn 150 mm aperture IT quadrupoles, Nb-Ti 150 mm D1 and 105 mm D2 separation dipoles, 90 mm Q4 and 70 mm Q5 matching quadrupoles.
- The high  $\beta$ -functions will amplify optical aberrations caused by field errors in these magnets which, in turn, may reduce dynamic aperture (DA). These effects have to be examined leading to specifications of field quality satisfying two main conditions: 1) they should provide a sufficient DA ( $\sim 10\sigma$ ) for both collision and injection optics, and 2) they should be realistically achievable.
- Estimates of achievable field quality in these magnets were obtained from magnetic field calculations and measurement data (see e.g. E. Todesco, “Field quality in the inner triplet and in the separation dipole”, LHC-LARP meeting, Frascati 2012, and CERN-ACC-2013-002 report). These estimates were used as a starting point for the optimization and subsequent specification of the new magnet field quality.
- The DA calculations were performed using long-term tracking in SixTrack.
- HL-LHC lattice layout SLHCV3.1b with settings for: 1) collision optics with  $\beta^*=15/15$  cm at IP1/IP5 and  $E = 7$  TeV, and 2) injection optics with  $E = 450$  GeV.

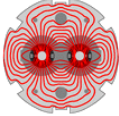
# Optimization

- The estimated field quality obtained from magnetic field calculations or measurement data is a starting point for optimization. It is also a target for the specifications since it is close to achievable.
- DA sensitivity to field errors is determined by performing DA scans versus individual  $a_n$ ,  $b_n$  terms.
- The terms which significantly reduce the DA are scaled down to satisfy an acceptable DA. However, the reduction is limited to less than a factor of 2 for compatibility with the achievable field quality.
- The optimization determined that for an acceptable DA in the collision optics, it is required to add the IT correctors for  $a_5$ ,  $b_5$ ,  $a_6$  error terms to the initial set of  $a_3$ ,  $b_3$ ,  $a_4$ ,  $b_4$ ,  $b_6$  correctors.

## Typical set-up of a SixTrack simulation:

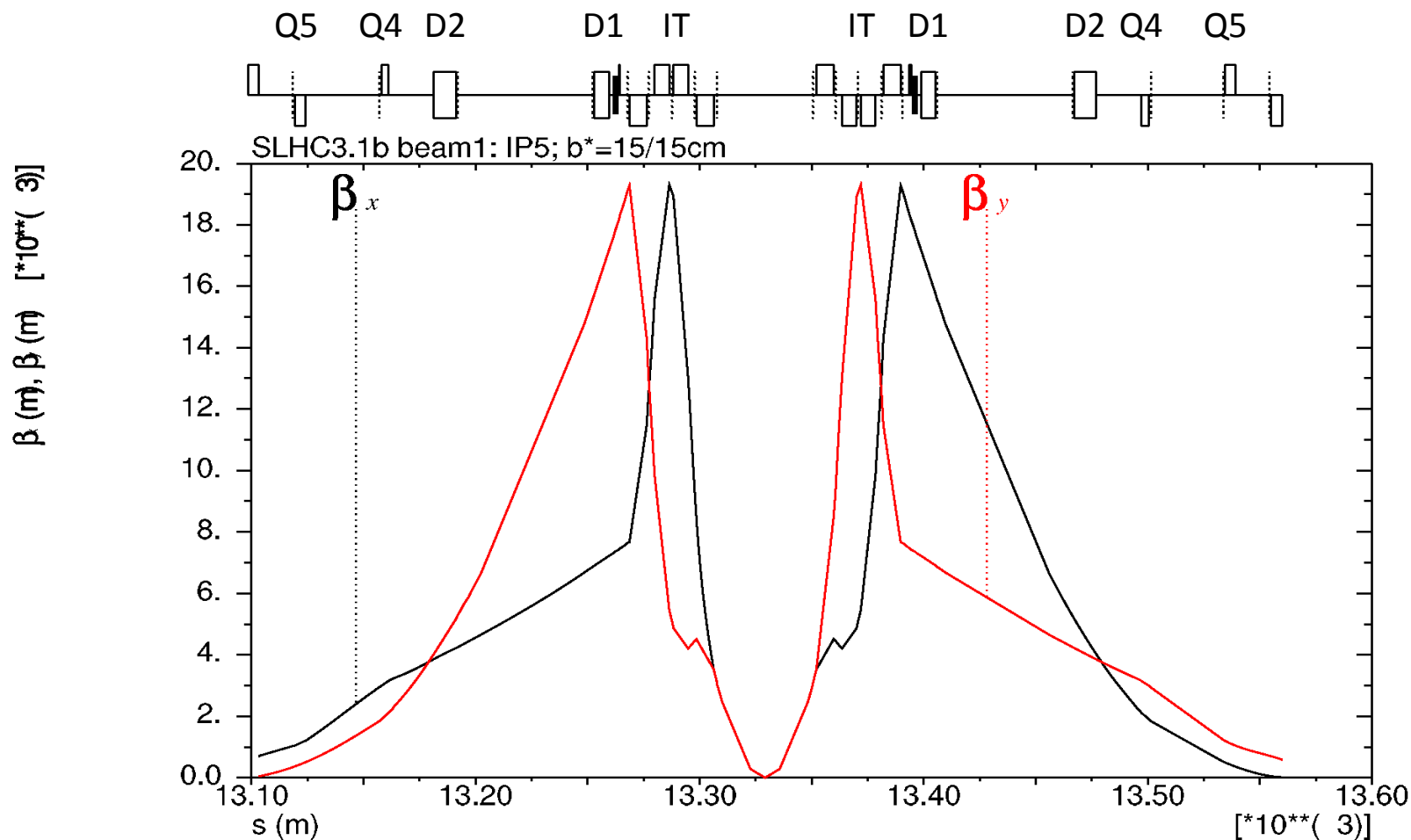
- 100,000 turns
- 60 random error seeds
- 30 particle pairs per amplitude step ( $2\sigma$ )
- 11 x-y angles
- Beam energy: 7 TeV (collision), 450 GeV (injection)
- Initial  $\Delta p/p$ :  $2.7e-4$  (collision),  $7.5e-4$  (injection)
- Tune: 62.31, 60.32 (collision), 62.28, 60.31 (injection)
- Normalized emittance =  $3.75 \mu\text{m-rad}$
- Arc errors and the standard correction systems are included
- IT non-linear correctors of order  $n=3-6$  are used in the collision optics
- Feed-down effects in the D1, D2 separation dipoles are included

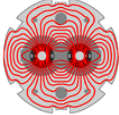




# Beta functions

$\beta$ -functions in the IT, D1, D2, Q4, Q5 magnets are significantly increased in the collision optics of the HL-LHC, thus enhancing beam sensitivity to field errors in these magnets. The IT non-linear field correctors help compensating the impact of low order IT and D1 field errors ( $n=3-6$ ).



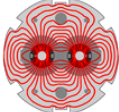


# Field quality specifications for IT quadrupoles at collision energy ( $r_0 = 50$ mm)

Blue values are estimates of the field quality based on magnet design. Red values are adjustments (reduced relative to the estimate) needed for sufficient dynamic aperture (DA).  
Reference table: “IT\_errortable\_v66”.

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.800	0.800		b3	0	0.820	0.820
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a5	0	0.430	0.430		b5	0	0.420	0.420
a6	0	0.310	0.310		b6	0.800	0.550	0.550
a7	0	0.152	0.095		b7	0	0.095	0.095
a8	0	0.088	0.055		b8	0	0.065	0.065
a9	0	0.064	0.040		b9	0	0.035	0.035
a10	0	0.040	0.032		b10	0.075	0.100	0.100
a11	0	0.026	0.0208		b11	0	0.0208	0.0208
a12	0	0.014	0.014		b12	0	0.0144	0.0144
a13	0	0.010	0.010		b13	0	0.0072	0.0072
a14	0	0.005	0.005		b14	-0.020	0.0115	0.0115

$$B_y + iB_x = 10^{-4} B_{ref} \times \sum_{n=1}^{\infty} (b_n + ia_n) \left( \frac{x + iy}{r_0} \right)^{n-1}$$



LARP

# Field quality specifications for IT quadrupoles at injection energy ( $r_0 = 50$ mm)



Estimated IT field quality, based on magnet design, is acceptable for DA at injection.  
Reference table: “IT\_errortable\_v66”.

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.800	0.800		b3	0	0.820	0.820
a4	0	0.650	0.650		b4	0	0.570	0.570
a5	0	0.430	0.430		b5	0	0.420	0.420
a6	0	0.310	0.310		b6	-16.0	1.100	1.100
a7	0	0.190	0.190		b7	0	0.190	0.190
a8	0	0.110	0.110		b8	0	0.130	0.130
a9	0	0.080	0.080		b9	0	0.070	0.070
a10	0	0.040	0.040		b10	4.15	0.200	0.200
a11	0	0.026	0.026		b11	0	0.026	0.026
a12	0	0.014	0.014		b12	0	0.018	0.018
a13	0	0.010	0.010		b13	0	0.009	0.009
a14	0	0.005	0.005		b14	-0.040	0.023	0.023

# Summary and plans

- DA sensitivities to field errors in the large aperture IT, D1, D2, Q4, Q5 magnets in the HL-LHC lattice (SLHCV3.1b layout) were evaluated for both collision and injection optics.
- The field errors were optimized to satisfy an acceptable DA ( $10\sigma$ ) leading to the new specifications in these magnets.
- It is confirmed that the IT non-linear field correctors of order  $n=3-6$  must be used to avoid tight low order field tolerances in the IT and D1 magnets in collision optics.
- The impact on DA from feed-down due to orbit offset in the D1 and D2 dipoles is found to be small.
- Field error terms in the IT, D1 and D2 magnets with large impact on DA at collision energy were identified. For an acceptable DA, their specification values were reduced (not more than a factor of 2) compared to the estimate based on magnet design.
- The presently estimated field quality in the Q4 and Q5 matching quadrupoles at collision energy is found acceptable.
- The estimated field quality at injection energy for the IT, D1, D2, Q4, Q5 magnets is acceptable.
- The next step is to verify these specifications using the next generation of the HL-LHC lattice layout HLLHCV1.0 and make adjustment if needed.



# Program Achievements - Timeline (1/3)

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- Mar. 2006      SQ02 reaches 97% of SSL at both 4.5K and 1.9K  
• *Demonstrates MJR 54/61 conductor performance for TQ*
- Jun. 2007      TQS02a surpasses 220 T/m at both 4.5K and 1.9K (\*)  
• *Achieved 200 T/m goal with RRP 54/61 conductor*
- Jan. 2008      LRS02 reaches 96% of SSL at 4.5K with RRP 54/61  
• *Coil & shell structure scale-up from 0.3 m to 4 m*
- July 2009      TQS03a achieves 240 T/m (1.9K) with RRP 108/127 (\*)  
• *Increased stability with smaller filament size*
- Dec. 2009      TQS03b operates at 200 MPa (average) coil stress (\*)  
• *Widens Nb<sub>3</sub>Sn design space (as required...)*

(\*) Tests performed at CERN





# Program Achievements - Timeline (2/3)

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- Dec. 2009      LQS01a reaches 200 T/m at both 4.5K and 1.9K  
• *LARP meets its “defining” milestone*
- Feb. 2010      TQS03d shows no degradation after 1000 cycles (\*)  
• *Comparable to operational lifetime in HL-LHC*
- July 2010      LQS01b achieves 220 T/m with RRP 54/61  
• *Same TQS02 level at 4.5K, but no degradation at 1.9K*
- Apr. 2011      HQ01d achieves 170 T/m in 120 mm aperture at 4.5 K  
• *At HL-LHC operational level with good field quality*
- Oct. 2011      HQM02 achieves ~90% of SSL at both 4.6 K and 2.2 K  
• *Special coil to test reduced compaction*

(\*) *Test performed at CERN*





# Program Achievements - Timeline (3/3)

Apr. 2012 HQ01e-2 reaches 184 T/m at 1.9K (\*)

- *Despite using first generation coils, several known issues*
- *Above linear scaling from TQ ( $240/120 \times 90 = 180$  T/m)*

Jun. 2012 HQM04 reaches 97% SSL at 4.6K and 94% at 2.2K

- *Successful demonstration of revised coil design*
- *Single-pass cored cable, lower compaction*

## Post 2012 Review updates:

Sept. 2012 LQS03 reached 210 T/m at 1.9 K (200 T/m target)

Dec. 2012 HQ02a test: 182 T/m at 4.5 K

- *98% SSL at 4.5 K*
- *improved performance with 2<sup>nd</sup> generation coils*

(\*) Test performed at CERN

